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Fusion of Sensor Data and Intelligence in FITS

Enrique Martí, Alvaro Luis, Jesus garcia
GIAA – Computer Science, UC3M
Colmenarejo, Spain
{aluis, emarti, jgherrer}@inf.uc3m.es

Susana Onate, Carlos Sanchez, Sergio González
Mission Systems – Engineering, AIRBUS MILITARY. Getafe, Spain
{susana.onate, carlos.n.sanchez, sergio.gonzalez}@military.airbus.com

Abstract—**The design and implementation of fusion systems working in real conditions requires functional and performance specification, analysis of information input and contextual domain, and development of testing and validation tools. This paper presents a fusion system recently developed to operate with EW and ISR sensors on-board of patrol aircraft, which must be fused with information from other collaborative entities and intelligence in databases. The paper describes the overall organization of the system developed, modules and the data flow. The characterization of data sources and core algorithms for data alignment, uncertainty representation and fusion management are detailed and validated in realistic situations.**

Keywords—Electronic warfare, ELINT/COMINT/ISR fusion, distributed fusion;

I. INTRODUCTION

Airbus Military develops Airborne Mission systems since more than twenty years ago and its Fully Integrated Tactical System (FITS) is currently operating in more than fifty aircrafts like C-212, CN-235, C-295 and P-3, focused mainly on Maritime Surveillance, Anti-Submarine Warfare (ASW) and Signals Intelligence (SIGINT). FITS is an airborne surveillance and tactical integration system that allows tactical crew to receive, manipulate and view in real time tactical data from a wide variety of sensors (Radar, ESM/ELINT, COMINT, Acoustic, Electro-optic, Data Links, etc) and navigation information from a variety of aircraft systems.

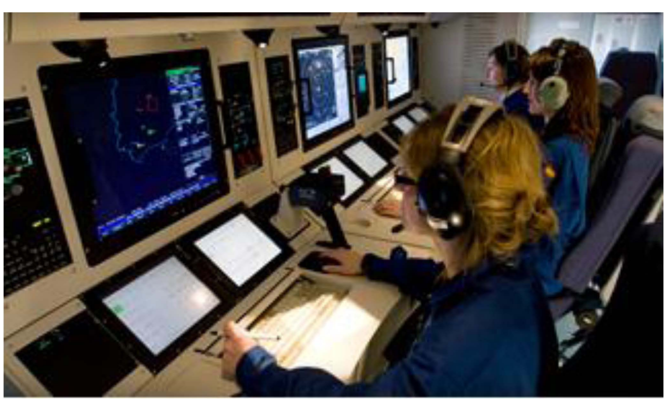

Figure 1. Fully Integrated Tactical System

The Multifunctional Consoles (MFCs) are the principal Human-Machine Interface (HMI) of the system. The consoles allow controlling the integrated mission sensors, displaying the information generated by them as well as composing the tactical situation depiction or performing computations. This results in an enhancement of situation awareness that facilitates decision making and improves the operational efficiency of the mission, turning the FITS in a complete and powerful Command and Control (C2) System.

Nowadays sensors are more and more powerful and Tactical Systems function is not only able to display and collect this information but also prioritize and fuse data from different sources in order to create a Global situation or Order of Battle (OB, description of all entities detected in the area of interest covered by mission). By means of a set of automatic algorithms and the use of Intelligence Libraries, Data Fusion System (DFS) provides FITS operators with an enhanced information in real time what reduces to the maximum extent the operator workload and minimizes human errors when interacting with the system.

This paper presents a system-level description of the recently developed Data Fusion Systems working with FITS data to improve the operator situation awareness. The paper reviews the functional requirements, global approach to design the fusion processes and some details about the key algorithms. Section II presents the architecture and main components of DFS, section III describes the inputs and basic operations before the fusion processes described in section IV. Section V describes the simulation and analysis utilities, illustrated with an example for analysis, and section VI concludes the paper.

I. ARCHITECTURE

The general structure of Data Fusion system is sketched in figure 2, including the available information sources and expected functions (detailed below).

A. Correlation

This subsystem is intended to compare the EW (electronic warfare) sources and decide if they correspond to the same emitter. It is based on signal parameters, available categories and spatial analysis of detections. As result, it provides the combined tracks (CESMO, *Coorperative Electronic Support Measures Operations)*, representing the estimation obtained after fusion of several correlated EW tracks, including the fused location and signal parameters.

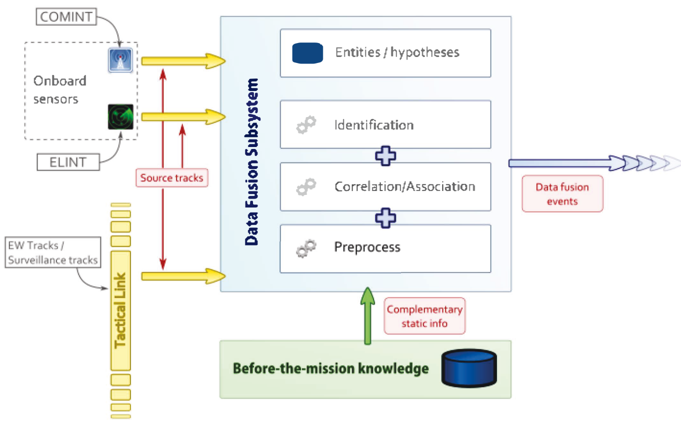

Figure 2. SDF inputs and functions

B. *Association*

In the context of this work, the association subsystem is in charge of comparing the time-space trajectories of different sources which may represent the same entity, detected by complementary sensors. A typical example is the association of radar and communication emitters located in a certain target (as a frigate), possibly extended with other ISR tracks provided by other sensors, if available. So, in this paper, "association" has a more specific meaning than the general sense in information fusion literature. The result of association is the set of "Platforms", containing the information fused from different sensors.

C. *Identification*

Finally, the identification module analyzes the correspondences between the tracking products of DFS with the static entities in the intelligence database. It uses both correlation and association processes to decide these correspondences and enrich the fusion with the available information in the static database.

II. INFORMATION SOURCES AND FUSION OUTPUT

The information available in the Data Fusion System can be categorized in several types accordingly to the sources:

- Navigation input: position, kinematics, attitude, etc.
- Input from onboard/airborne "electronic warfare" sensors and cooperative network (ELINT reports including target id, signal parameters, localization info (line of bearing, area of uncertainty, etc.)
- Other sensor inputs (COMINT): target id, descriptive fields, localization, etc
- Messages from collaborative units (tactical data link). Target id, signal parameters, location, etc.
- Other surveillance input (ISR sensors, AIS, etc.): target id, descriptive fields, localization, etc
- Intelligence: characterization of well-known entities (Emitters/Platforms) (identification, position, environment)

AIRBUS Military – EADS/CASA. Contract DFS-FITS (2011-2013).

The system keeps "local tracks" corresponding to each available data source and checks their consistency along time, to keep all tracks corresponding to the same targets. To do that, tracks have to be timely aligned and compared. Depending on the types of sources, two basic processes are carried out for track comparison and association: in the case of EW tracks, a correlation process is carried out to form CESMO tracks associated to radar emitters, considering the specific features of ELINT data and bearing information. In other cases a time-space association process is done to group the single-sensor tracks in the fused system tracks, named as platforms.

The first problem of DFS is building groups of tracks from different sources corresponding to the same target, in order to fuse them and obtain an improved estimation about the entity. In the particular case of EW tracks association, we name this as "correlation" problem, whose outputs are the CESMO tracks. Figure 3 illustrates the situation of grouping the tracks provided by 4 sources (including on-board sensors and collaborative entities):

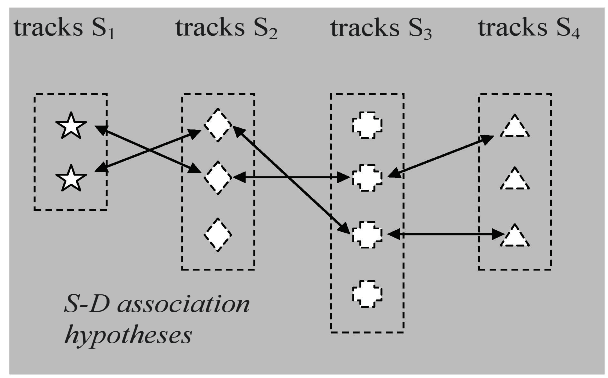

Figure 3. S-D Multi-track association formulation

Theoretically, the correlation of local tracks to form the system global tracks is potentially very complex [1,2], it would require a search of which subsets of local tracks may refer to the same target (the theoretical number of grouping hypotheses is given in [3] considering the uncertainty in the number of real targets moving in the scenario). Obviously, a solution with enumeration of all association hypotheses in each fusion cycle is not affordable, so the system assumes certain simplifying conditions and discrimination capability in the available data (signal parameters), as will be described later.

A. *Spatial Alignment*

The selected fusion coordinates are expressed with respect to a local tangent plane (LTP frame), with the origin located in the selected position at ellipsoid surface (fusion center) and XYZ axes pointing respectively to East, North and Up (ENU). This system is the referred to a fixed reference at Earth surface, usually fixed in a reference position related with flight mission (if the trajectory is not very long, otherwise, the reference would change along the mission trajectory).

In order to carry out the coordinate transformations, the basic conversions are applied to transform geodetic coordinates (latitude, longitude, height) to ECEF Cartesian coordinates and then to local tangent plane, ENU, (x_l, y_l, z_l), taking as parameter also the reference geodetic position, (lat_{orig}, lon_{orig}, h_{orig}). Additionally, other transformations are needed to change vectors and directions with respect to different local coordinates systems. For instance, the velocity is referred to the position of object in the local North direction, and so it is needed a transformation from this local plane to the fusion coordinates. Analogously, the angles are referred to local North and must be transformed to the fusion plane (for velocity heading and line of bearing measurements).

With respect to data, DFS can manage alternative representations of positioning data, independently of the coordinate framework. One is the fix, a very accurate position, with no uncertainty associated. Conversely, an AoP (*Area of Probability*) describes an uncertain location as an iso-probable area that contains the true position with a high confidence (usually in the range 90-95%). Finally, a LoB (*Line of Bearing*) describes the position of an object that has been detected using a sensor that provides only directional information about origin of emission. It can be seen as a straight line with its origin in the place where the observer entity is located.

The positions and associated uncertainties (AoP) can be expressed in the fusion coordinates with conventional transformations. An additional problem with the last type of localization is that the local plane describing the LoB area is perpendicular to local plane but not to fusion plane, so the uncertainty depends on the real height of object, which is generally unknown. Figures 4,5 illustrate the problem and associated uncertainty region (a band around LoB projection).

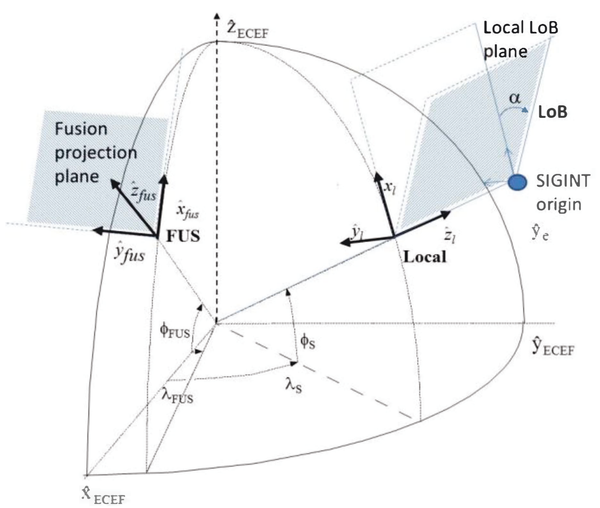

Figure 4. Transformation of LoB region from local to fusion plane

The misalignment between local and fusion North implies that the projection on fusion plane is not vertical, but an uncertainty region appears, which depends on the height difference between SIGINT sensor and emitter. Assuming a worst case situation of h (the emitter is on ground), the maximum width of uncertainty area can be bounded with expression:

$$\cos\gamma = \vec{z}_l \cdot \vec{z}_{fus}$$

$$w = h\frac{\cos\gamma}{\sqrt{1-\cos^2\gamma}}$$

In practice, this uncertainty can be significant with emissions detected from collaborative entities operating very far from fusion center (thousands of NM).

B. *Time Alignment*

In this environment, the DFS process runs as an external system linked with the FITS. This decoupled approach allows full processing capabilities for the DFS and also avoid undesired behaviors in the critical FITS system when the computing power demand is increased due to high-load environments. However, this implies handling real-time communications both for receiving information from FITS sensors, and transmitting fusion events once the input data is processed. All the communications in this scheme are done in a binary format in order to achieve high efficiency. The FITS system is the responsible for feeding the DFS with the real-time information captured from each on-board sensor and tactical link, which is in its turn processed in the fusion cycle. As the incoming information arrives in an asynchronous way with respect to the DFS fusion cycle (the fusion cycle can be running as new incoming information is being received from the network link), it is necessary to buffer the information before its processing. This makes it necessary to use concurrent threads of execution for handling real-time communications and fusion cycle processing.

So the first thing the fusion cycle does is to collect all the buffered information received while the previous fusion cycle was running. In order to ensure that this little delay for processing the information, plus the delay introduced in the communication process does not affect to the fusion quality, it is considered the time when the information was generated rather than the time when the information is being processed. This is because each information piece has a field with the creation and update timestamp filled by the FITS. All the messages transmitted in this way between the FITS and the DFS are transmitted through network sockets. The main messages received in the DFS are summarized in figure 5, which mainly correspond to input source tracks and navigation data. There are other messages involved in the process like those for change the initial configuration parameters in the DFS, change its running state, and also some other messages generated by the operator that can force or forbid correlations and associations. All these messages are also buffered before its processing as they can modify the DFS internal state. As shown in figure 5, the DFS is also responsible of sending information back to the FITS like the fusion output and the internal DFS state. This output information is not buffered in the DFS in any way, so all the updated information in the DFS after a fusion cycle is delivered immediately.

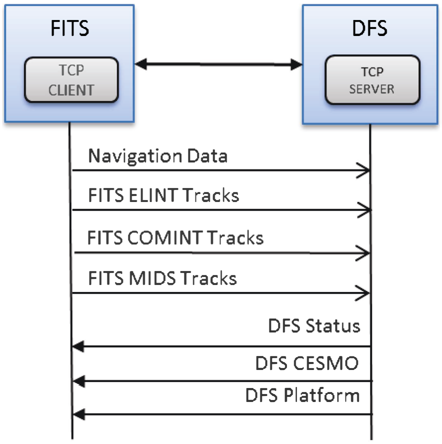

Figure 5. Main binary messages transmitted between FITS and DFS

III. OVERVIEW OF FUSION ALGORITHMS

Fusion algorithms calculate their output based on the following aspects of input source tracks:

- Signal features (electronic emitters)
- Physical location and kinematics
- Threat classification and similar features
- Estimation of information quality

Next subsections illustrate some aspects of the problem, and the implemented solutions. It is important to note the particularities of the proposed problem, that in many cases discouraged adopting a more academic, standard solution.

A. Signal correlation

The fusion of ELINT and EW tracks (provided by tactical link) is mainly based on their signal features. The features considered include numeric values such as frequency, pulse rate interval or pulse width.

When available, extended information is also used to correlate/associate input source tracks. This extended information is usually composed of enumerated fields, as in the case of the emitter scan pattern, or the characteristics of the pulse repetition frequency (staggered, with jitter, etc.). Extended information can be valuable for its discriminative power. However, determining the compatibility between optional, discrete valued variables can be non-trivial, imposing sometimes a case-by-case logic. We can find a remarkable example in the case of signal modulation: the information provided by ELINT onboard sensors is composed by several Boolean features (continuous/pulsed, chirp present…) and some enumerated fields, all of them optional (can have a value or been unknown). On the other hand, modulation information acquired over Tactical Link (EW tracks) is restricted to a single enumerated field (also optional). Some values of this enumerated field describe concrete combinations of the fields of an ELINT track, but some others cannot be expressed by ELINT sensors: they are exclusive of MIDS tracks.

In summary, the available information for deciding whether two entities must be fused is (a) heterogeneous, (b) not always available. In general, it is possible to establish a similitude metric between pairs of tracks, but makes difficult to apply some strategies as efficient clustering algorithms. The similarity score between two different tracks must include a measure of information overlapping, indicating the "amount of information" that is present in both tracks at the same time. The decision on whether these entities must be fused will take into account the degree of compatibility, but also the number of indicators that contributed to calculating it.

B. Physical location compatibility

Fusion decisions are subject to geographic compatibility when this information is available. Location information is provided by heterogeneous sources, causing input data to have different qualities.

Input tracks can have their position defined in three forms:

- Fix: specific location with little or no uncertainty. Usually coming from previously available data, as intelligence databases.
- Line of Bearing (LoB): bearing-only information, as provided by airborne directional sensors. The bearing error is uniformly distributed inside an angular bound marked by a quality parameter.
- Area of Probability (AoP): elliptical area that contains the target with a high confidence. According to sensor suppliers, AoPs are considered to describe track location as a uniform probability distribution, instead of the classical Gaussian distribution.

The factors taken into account for designing a location compatibility algorithm are (a) the heterogeneity of location types/qualities (b) error distributions are unknown or roughly approximated, (c) external pieces of information (Tactical Link) can be correlated, (d) the period of information renewal, ranging between 1 second and up to several minutes.

Individual aspects of this problem have been treated before. Fuzzy reasoning has been applied in [4] for fusing locations coming from different sensors, while also mitigating the problem of including old information. In [5], authors deal with the problem of fusing locations when their covariance can be correlated.

Having to deal with all the aspects of the problem at the same time our priority is determining, with the largest confidence, if two locations actually refer to the same object in the real world. Since location uncertainties are specified as uniform probability distributions, we have preferred a geometrical approach. As a result, a new intermediate type of location is used: convex polygons are powerful enough to represent the intersection of any combination of fixes, AoPs and LoBs. They also make possible to augment the uncertainty of a location if required. Two locations are considered to be geographically compatible if their equivalent polygons have a non-empty intersection. This result is complemented with a quality indicator calculated as the ratio between the input areas and the calculated intersection. The resulting area can be transformed back to Fix, LoB or AoP.

A particular case is shown in figure 6. Three tracks representing the same object must be fused. Two of the tracks provide location as an AoP and the other as a LoB. Although areas do not strictly intersect, they are expanded by a factor that depends on their quality and other indicators. The resulting intersection is transformed back to a suitable representation (an AoP in this case, check table 1) and usually expanded again to account for the errors in the process.

The final decision on whether those tracks must be fused or not, and the procedure for calculating the final estimated location depend on many other factors: alternative fusion decisions, quality of source information, *a priori* knowledge in the static database, etc. The fusion criterion is conservative [6], accuracy about fused locations tends to be pessimistic in order to increase stability and avoid misguiding system operators.

Table 1 Geometric entity resulting from the intersection of two other areas

	Polygon	AoP	LoB	Fix
Fix	Fix	Fix	Fix	Fix
LoB	Polygon	AoP	Polygon	
AoP	Polygon	AoP		
Polygon	Polygon			

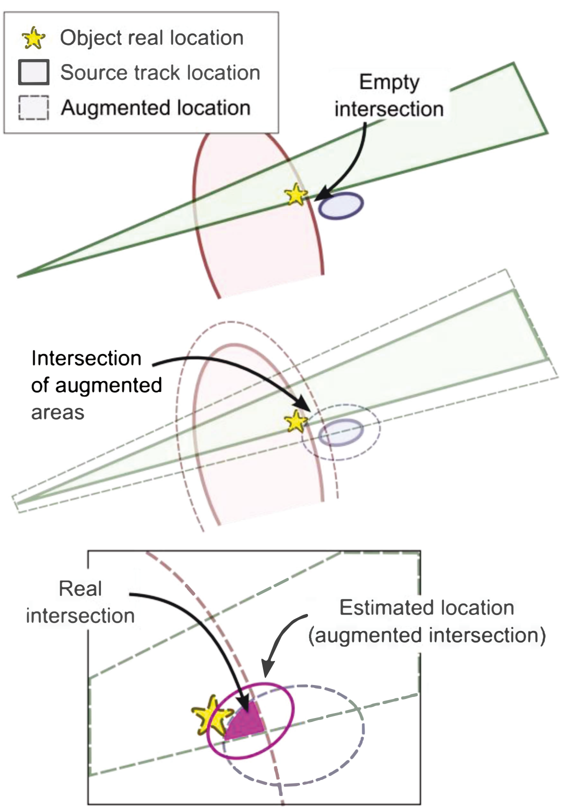

Figure 6. Location estimation with heterogeneous and biased information

C. *Fusion Management*

An effective track management process has been implemented as a complement of correlation and association processes, following a similar approach to other fusion systems working in realistic conditions [7]. Multisensor tracks (CESMO tracks and Platforms) are initialized as hypotheses, to be confirmed when there is enough accumulated evidence of its existence and no conflict with other hypotheses. Furthermore, the linked local tracks to be fused are periodically analyzed to correct the potential errors in this association (de-fusion), but until that moment the association decisions will be maintained, avoiding the enumeration of groups as much as possible. Figure 8 shows the organization of entities used in DFS.

The basic aspects of the algorithm are:

- Comparison of single-sensor tracks: they have to be aligned and compared, considering the characteristics of the different nature of available sources (ELINT, COMINT sensors)
- Initialization of tentative fused tracks (CESMO and Platforms). A set of criteria is established to confirm the fused tracks (persistent association and quality)
- Management processes at local and global levels (initialization, deletion, de-correlation, un-association)

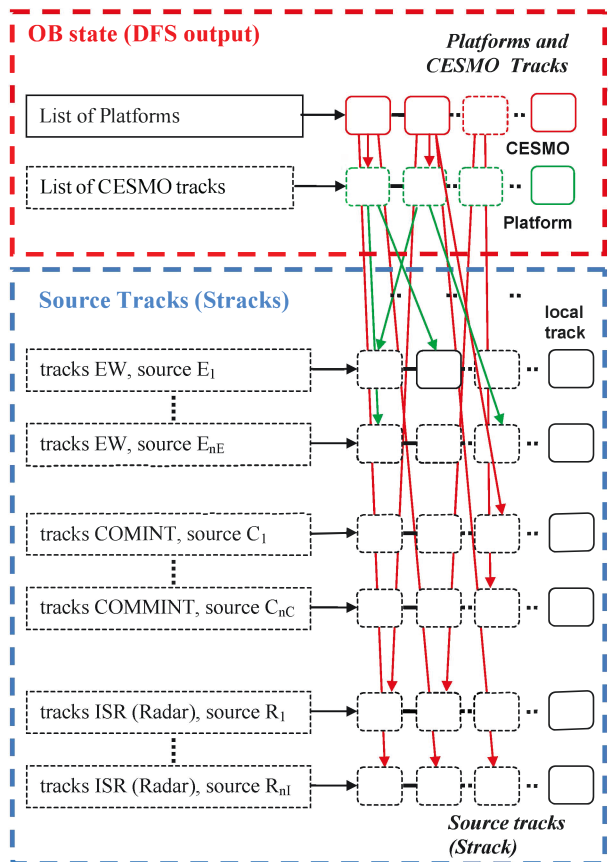

Figure 7. Internal representation of OB in DFS *Three types of global tracks: Stracks, CESMO tracks and Platforms*

It follows a decentralized hierarchical architecture where the system tracks are linked to source tracks which are grouped after comparison and combined to generate the fused output. The source tracks provided by on-board sensor or tactical link are kept in a first level, organized in separate lists corresponding to different sources (both internal sensors and each cooperative entity providing data through the tactical link). Then, these source tracks are combined at two levels: those coming from electronic war sensors (EW tracks) are combined to form the CESMO tracks, each one referred to a single emitter detected by several EW sensors, and platforms, when different types of sensors detect the same target (a CESMO can be a component of a platform). DFS will update periodically its internal state by processing the input (Stracks). In each fusion cycle, the local tracks are updated (copied using the track identification), and then the fusion processes are performed to update the CESMO tracks and platforms.

The approached fusion problem has been segmented in layers. These layers are coupled, meaning that decisions at higher levels are greatly influenced by those at lower layers. However, the most common scenarios do not pose a big data association challenge: simple strategies usually deliver the optimal result. On the other hand, errors are commonly caused by sensor inputs that are either incomplete or faulty.

The preferred implementation consists on a greedy strategy with periodic revisions of fusion decisions. In a first step, the locally best decision is assumed. A periodic fusion management process acts over the resulting configuration, taking care of the following cases:

- Amending decisions that were right in the past but are no longer legal with current evidences. For example, extracting incompatible components from high level entities can result in deleting those entities.
- Merging high level (composed) entities when they have compatible components.
- Splitting high level entities into two or more entities (also composed)
- Reconfiguring the components of pairs of high level entities (component transference) when this improves the global quality of the fusion.

With this approach, we avoid the potential complexity of keeping a hypothesis tree representing all the combinations that could explain the data received in a certain scenario. Results are correct in all the tested scenarios, with just a few temporal errors that are corrected within the next sensor update (or at most in the next 2 cycles).

IV. ILLUSTRATIVE ANALYSIS SCENARIO

A. *Simultion of SIGINT inputs*

Airbus Military has developed a complete testing system in the laboratory that includes scenario and signals generation, stimulation and monitoring in order to perform a complete validation of SW releases before being installed and tested in aircrafts. Figure 8 illustrates the available equipment, at the left side are the servers with simulation, communication and process management, and the consoles at right-side are operator positions to visualize navigation state, sensors output, tactical data link, etc.

Figure 8. Test bench for scenario simulation and system validation

The combination of sensor development equipment with complex scenarios and aircraft model provides the same airborne interface and data to allow extensive tests that minimize the risks of failures when SW is tested in flight.

B. *Visualization of output and analysis tools*

In a complex fusion system like the one described in this work, there are usually several heterogeneous sensors providing different kinds of information. This diversity of information may complicate the verification of the different tiers composing the fusion system, specially the ones related with the data input, as it is composed by several chains of interrelated processes to generate a single fused output. In order to properly analyze and debug the DFS, it has been necessary to use two different mechanisms in the management of this information.

On the one hand, it is necessary a method for recording and playing all the information perceived from the real environment. The recording of mission scenarios allows a systematic re-use of the incoming information for a detailed analysis of each fusion algorithm in the same input conditions. This implies storing all the sensing data received in the DFS with its corresponding timestamp at receiving. The timestamp information along with the raw data is used later in a process that simulates the real environment, but in this case the data comes from a recording file instead of the real sensors. This kind of recording method provides the repeatability required to finely debug the result of each tier or algorithm with the same input conditions. Figure 10 shows the outline of the different data flows used in this verification process. In this case the DFS can be fed both with the information coming from the real environment (Real Input), and a simulated input (Sim Input) that reads the data from previous recordings.

On the other hand, in the DFS verification process is needed a component for displaying the information on the screen computer. In this case, as the DFS output information is referred in WGS84 coordinates, the best option to check whether the system is running as expected is by displaying incoming information and fusion output together. This is achieved by projecting the geographical information onto a map representation. As can be seen in figure 10, the DFS input information apart from its recording through the Input Log module for later playing, it is connected to a different module that can achieve its map visualization in real-time. This module is represented in the figure as the Display Link, and is also able to store all the incoming drawing information for a posteriori analysis without having to perform the whole data fusion process. The information displayed by this module is mainly related with the geographical shapes managed by the DFS, like Fix, LoB, AoP, and Polygon. Each shape has its own identifier (normally the track identifier) and can be represented with an arbitrary color, an identifying label like the track name, and finally metadata information.

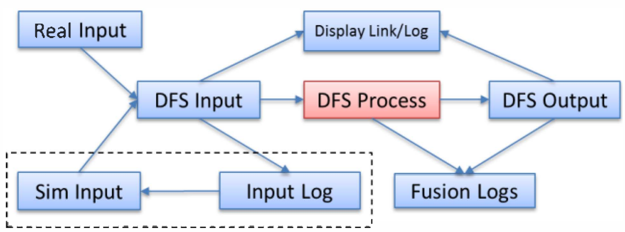

Figure 9. Main incoming and outgoing data flows used for data fusion analysis/debugging

Metadata is presented in a table when the identifying label is clicked, and can contain useful information to help in the DFS debugging processes, like signal parameters, output track components, last update time, and so on. This module is also connected to the DFS fusion output, which allows the overlapping of processed fusion output over the input information. This way is easier to detect when the fusion output is working as expected, and the track positions intersections are fine. A sample screenshot of this tool connected to the DFS process is shown in figure 11. In this case, there are different source tracks with LoB and AoP geometries, and a single fused track (in black). So this module can represent in real-time the internal state of the DFS process, as all the incoming and outgoing information is displayed over the map. Additionally other valuable information like the navigation data can be displayed in this module, so it is easy to see the aircraft position along its flight.

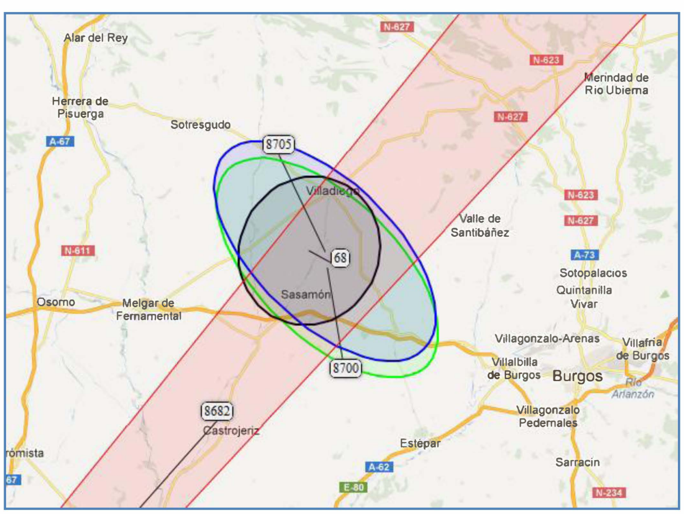

Figure 10. Example of the map projection used in the Visualization Link to display data fusion state in real-time.

This Display Link is running as an external process to the DFS system so the drawing load does not interfere in the DFS performance, as it is completely decoupled from the processing core. The communication is achieved using network sockets that can be easily disabled when the DFS debugging processes are ready and the system is running in the aircraft.

V. EXPERIMENTS AND VALIDATION

The implemented system has been subject to intensive testing, validating functional and non-functional requirements. Functional requirement validation has been performed over different simulated scenarios for a total of several hours of flight. Each scenario features tens/hundreds of entities detected by a variable number of collaborating units, that must be fused or not based on particular features. The tested functionality include creation, deletion, modification, merging and splitting of fusion products (CESMO tracks, platforms). An example is shown in Fig. 11.

Besides, computational performance has been evaluated in scenarios with several hundred entities, detected by up to 5 collaborating units at 1Hz rate. This results in a very high message ratio that usually surpass the specification. The implementation is fast enough to integrate the incoming information in real time.

So, Figure 12 shows an intermediate scenario with 40 entities in a densely populated area. Only one sensor reports entities as areas of probability, while the others provide bearing-only information. This introduces a high number of ambiguities that must be resolved by the DFS, increasing the computational load. The entities are marked by numbered labels in the center of the images. Lines of bearing emerge from the 4 collaborating units surrounding the cluster of targets. The DFS is capable of processing the 200 messages per second of this scenario with an average load below 25%.

I. CONCLUSION

This work presented a recently developed fusion system operating on-board with EW and ISR sensors, combined with the messages from collaborative entities and static databases. The key system-level and algorithmic aspects have been explained, and validated with available simulation and analysis tools developed for this environment. A set of tests were carried out to show that all elements work properly (signal parametric correlation analysis, position-related, kinematic-related and functional-related association algorithms work properly). This testing environment provided valuable conclusions and a good workbench to test the robustness of the involved algorithms.

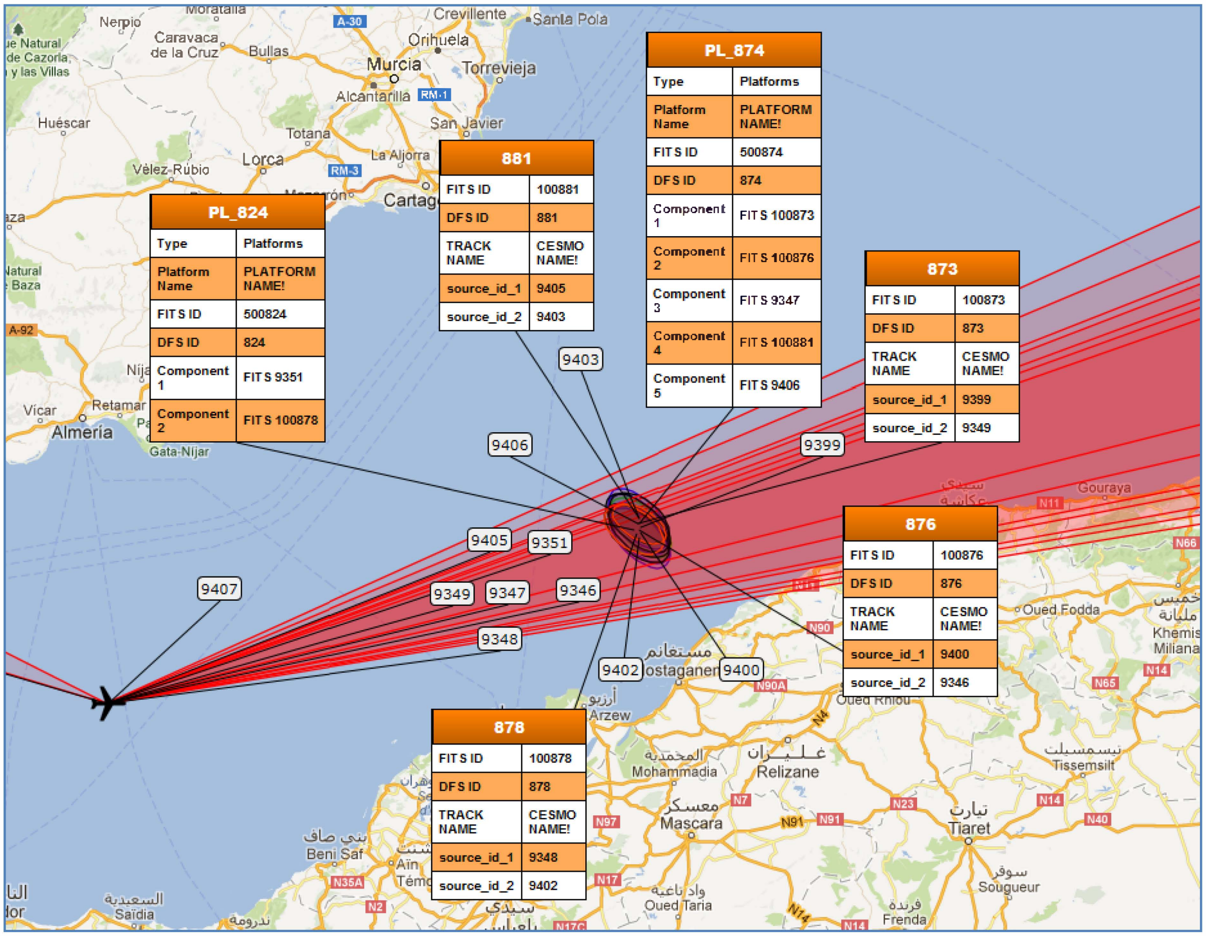

Figure 11. Complex validation scenario: 12 source track of mixed sources are arranged in 4 CESMO tracks and 2 platforms

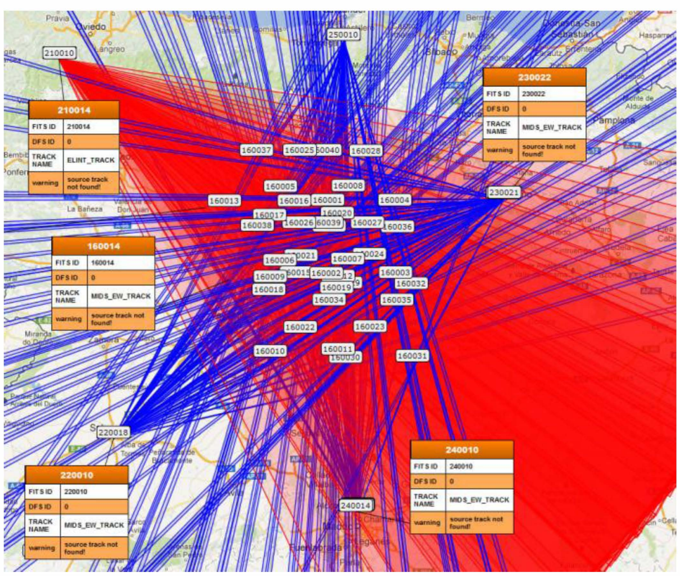

Figure 12. Load test featuring 40 targets detected by 5 sensors.

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